



A 3-D Magnetic Analysis of a Linear Alternator for a Stirling Power System

Steven M. Geng and Gene E. Schwarze
Glenn Research Center, Cleveland, Ohio

Janis M. Niedra
Dynacs Engineering Company, Inc., Brook Park, Ohio

The NASA STI Program Office . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the Lead Center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- **TECHNICAL PUBLICATION.** Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA's counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.
- **TECHNICAL MEMORANDUM.** Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.
- **CONTRACTOR REPORT.** Scientific and technical findings by NASA-sponsored contractors and grantees.

- **CONFERENCE PUBLICATION.** Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.
- **SPECIAL PUBLICATION.** Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.
- **TECHNICAL TRANSLATION.** English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized data bases, organizing and publishing research results . . . even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI Program Home Page at <http://www.sti.nasa.gov>
- E-mail your question via the Internet to help@sti.nasa.gov
- Fax your question to the NASA Access Help Desk at (301) 621-0134
- Telephone the NASA Access Help Desk at (301) 621-0390
- Write to:
NASA Access Help Desk
NASA Center for Aerospace Information
7121 Standard Drive
Hanover, MD 21076



A 3-D Magnetic Analysis of a Linear Alternator for a Stirling Power System

Steven M. Geng and Gene E. Schwarze
Glenn Research Center, Cleveland, Ohio

Janis M. Niedra
Dynacs Engineering Company, Inc., Brook Park, Ohio

Prepared for the
35th Intersociety Energy Conversion Engineering Conference
sponsored by the American Institute of Aeronautics and Astronautics
Las Vegas, Nevada, July 24-28, 2000

National Aeronautics and
Space Administration

Glenn Research Center

Acknowledgments

The authors wish to acknowledge the Stirling Technology Company for providing hardware information and test data relative to the DOE/STC Technology Demonstration Converter.

This report contains preliminary findings, subject to revision as analysis proceeds.

Trade names or manufacturers' names are used in this report for identification only. This usage does not constitute an official endorsement, either expressed or implied, by the National Aeronautics and Space Administration.

Available from

NASA Center for Aerospace Information
7121 Standard Drive
Hanover, MD 21076
Price Code: A03

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22100
Price Code: A03

A 3-D MAGNETIC ANALYSIS OF A LINEAR ALTERNATOR FOR A STIRLING POWER SYSTEM

Steven M. Geng and Gene E. Schwarze
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Janis M. Niedra
Dynacs Engineering Company, Inc.
Brook Park, Ohio 44142

ABSTRACT

The NASA Glenn Research Center and the Department of Energy (DOE) are developing advanced radioisotope Stirling convertors, under contract with Stirling Technology Company (STC), for space applications. Of critical importance to the successful development of the Stirling convertor for space power applications is the development of a lightweight and highly efficient linear alternator.

This paper presents a 3-D finite element method (FEM) approach for evaluating Stirling convertor linear alternators. Preliminary correlations with open-circuit voltage measurements provide an encouraging level of confidence in the model. Spatial plots of magnetic field strength (H) are presented in the region of the exciting permanent magnets. These plots identify regions of high H, where at elevated temperature and under electrical load, the potential to alter the magnetic moment of the magnets exists. This implies the need for further testing and analysis.

INTRODUCTION

Early linear alternator designs developed under the NASA Civil Space Technology Initiative (CSTI) generally used rare earth permanent magnets attached to a moving plunger. The harmonic motion of the magnets between the two gaps formed by the inner and outer stator laminations generated a sinusoidal flux in the stator. The sinusoidal flux then induced a voltage in the coils, which were wound inside the outer stator. The magnetic flux path through any of the stator laminations

was coplanar with the axis of mover motion; therefore, the designs were somewhat symmetric about their axis of motion. In these early linear alternator designs, a 2-D, finite element method (FEM) analysis was found to adequately model the magnetic fields.

Figure 1 shows a cross-section of the linear alternator designed for the Space Power Demonstrator Engine (SPDE), which was developed in the 1980s by Mechanical Technology, Inc. (MTI) of Latham, New York. Reference 1 provides a discussion on the 2-D analyses that were performed. Reference 2 shows that the analytical open-circuit RMS voltage (i.e., theoretical value) of the SPDE linear alternator was within a few percentage points of the measured values over a wide frequency range.

Current linear alternator designs being developed for the Stirling radioisotope power systems for deep space missions feature stationary rare earth permanent magnets attached to the stator laminations. These designs obtain a sinusoidal, reversing magnetic flux perpendicular to the planes of the stator coils by varying the reluctance of the flux path, as seen by the individual magnets. One coil is wound around each of the stator legs. A sinusoidal voltage is induced in the coils as the moving plunger (or mover) oscillates adjacent to the permanent magnets. These designs are typically symmetric about the axis of motion to the quarter section and, as a result, a 2-D analysis can not accurately model the magnetic fields. In addition, the magnetic flux path is perpendicular to the axis of mover motion, which further complicates the issue. Linear alternators of this design are better modeled in 3-D.

Figure 2 shows a cross-section of the linear alternator designed for the 55W Technology Demonstration Converter (TDC), which was developed in the 1990s by Stirling Technology Company (STC) of Kennewick, Washington, for the Department of Energy (DOE). A more detailed description of the TDC is given in References 3 and 4. The linear alternator model and results discussed in this paper are based on this STC 55W TDC linear alternator design.

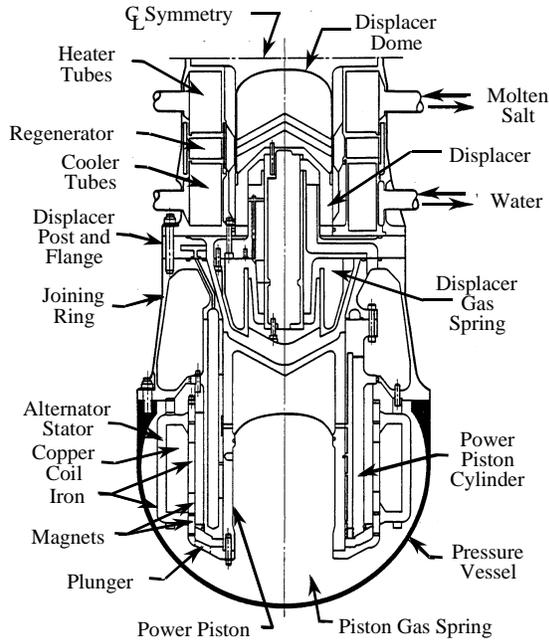


Figure 1 – Cross-section of Stirling Power Demonstrator Engine (SPDE).

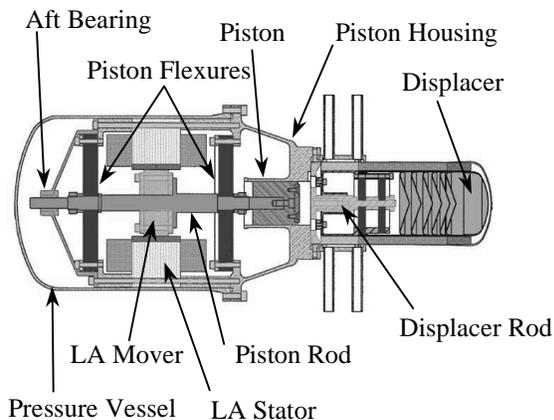


Figure 2 – Cross-section of STC's 55W Technology Demonstration Converter (TDC).

OBJECTIVE

The objective of this work was to develop a numerical analysis model that could aid engineers in the design, development, evaluation, and understanding of advanced linear alternators.

LINEAR ALTERNATOR MAGNETOSTATIC MODEL

A three-dimensional magnetostatic model of STC's 55W linear alternator was developed using Ansoft's Maxwell 3-D finite element method (FEM) software (Ref. 5). The magnetostatic model consisted of a quarter section of the linear alternator and included the following components: 1) ¼ stack of Hyperco-50 mover laminations, 2) Neodymium-Iron-Boron half-magnets, 3) ¼ stack of Hyperco-50 stator laminations, and 4) copper half-coils. Since the actual hardware is symmetric to the quarter section about the axis of motion, only a quarter section was needed in the model.

Figure 3 shows the flux density (B) and field strength (H) data used in the model for the Hyperco-50 mover and stator laminations. The data shown in this plot was measured at the NASA Glenn Research Center. For illustrative purposes in the FEM model, a remanence B_r of 1.26 Tesla and a coercive force H_c of -931 kA/m were assumed. These values are consistent with the STC specifications for the magnets and are similar to the properties of UGIMAX 37B at 23°C.

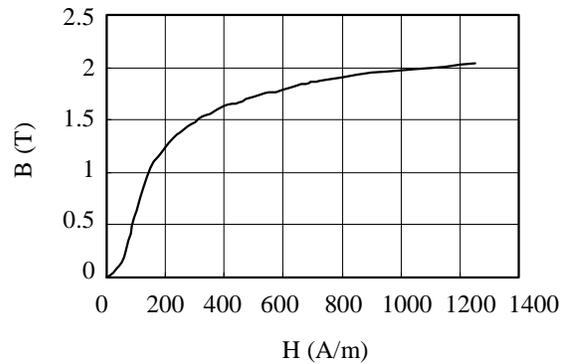


Figure 3 – BH Curve of Hyperco-50.

The primary model parameter of interest for verification with experimental data is the magnetic field parallel to the axes of the coil windings. It is this value of magnetic flux that is used to calculate the open-circuit voltage. To reduce the numerical error associated with the FEM mesh that is used to calculate the magnetic flux, namely the mesh for the coil, stator,

and coil/stator gap, 9 cut-planes were defined along the axis of the coil. The 9 cut-planes are shown in Figure 4. The model was set-up to calculate and average the magnetic flux normal to each of these cut-planes to obtain an overall average flux parallel to the axis of the coil.

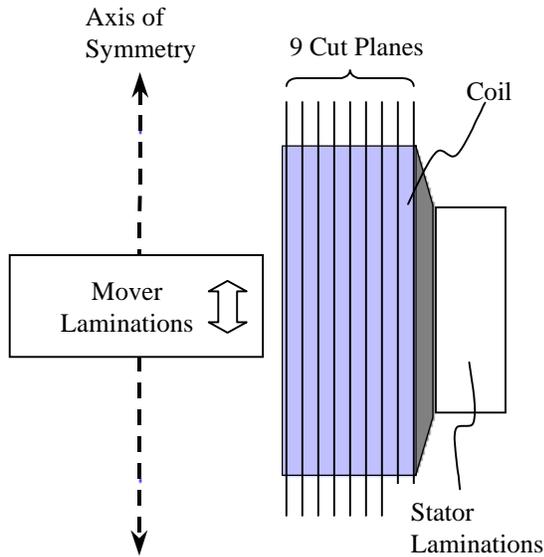


Figure 4 – Cut-Planes Through Coil Used to Calculate Average B Perpendicular to Coil Plane.

Magnetostatic flux solutions for a series of 13 different mover positions were generated. Faraday’s Law of induction was then used to calculate the induced electromotive force (emf) in the linear alternator coil windings at the 13 mover positions. The calculated induced emf was then curve-fit, using the TableCurve software. The open-circuit RMS voltage was calculated using the amplitude of the curve-fit solution.

The linear alternator model being a static simulation, eddy current effects due to the mover motion could not be calculated. However, neglecting the eddy current effects should not introduce large errors to the static solutions, since the mover oscillates at a low frequency (≈ 80 Hz) and all of the magnetic flux conducting structures were laminated (except for the magnets).

RESULTS

Internal State of Magnets

Figure 5 shows the demagnetization curves estimated for the UGIMAX 37B magnets at 23°C and 75°C. The 23°C demagnetization curve was used in the magnetostatic analysis, since STC measures the linear

alternator open-circuit voltage with the magnets at room temperature. Several load lines are shown in this figure with respect to one particular magnet. The load lines representing the mover positioned adjacent to this magnet and away from this magnet (i.e. at the ends of the mover stroke) were calculated based on the magnetic flux density B and magnetic field strength H averaged over the volume of the magnet. For the case where the mover is positioned adjacent to the magnet, the average load line is a fairly good representation of the internal operation of the magnet, since B and H are then somewhat uniform. But for the case where the mover is positioned away from the magnet, large variations in H exist. The average load line in this case may indicate a false margin of safety relative to demagnetization. Load lines for small, localized areas of the magnet may approach the critical knee where demagnetization can occur.

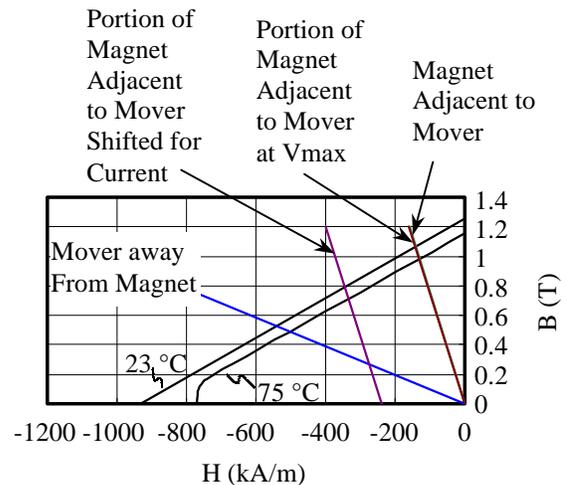


Figure 5 – Demagnetization Curve for UGIMAX 37B NeFeB Permanent Magnets along with Load Lines for the 55W TDC Linear Alternator.

Figure 5 also shows a load line for one of the magnets at the mid-point of the mover stroke, which corresponds with the maximum induced voltage in the coils. In this case, approximately half of the magnet is positioned adjacent to the mover. This load line was calculated based on the average B and H for only the portion of the magnet positioned adjacent to the mover. The reason for averaging over only this portion is that it is only this portion that is within the magnetic circuit at the mover mid-stroke position. This load line practically falls right on top of the magnet-adjacent-to-mover load line described earlier. The load line was then shifted by -238 kA/m (number of turns multiplied by the peak current divided by the thickness of the

magnet and air gap) to account for the demagnetization effect caused by current flowing through the coil. Equations derived by Niedra (Ref. 6, Appendix A) were used to verify the load lines for the covered portions of the magnet and agreed well with the FEM model. Based on the load lines shown in Figure 5, it appears that the self-demagnetization effect of the uncovered magnets are more of a concern than the demagnetization effect caused by current flowing through the coils. A closer look at localized areas of the magnets is needed.

Figure 6 is a plot of magnetic field strength (H) vs. distance along one stator leg for the mover positioned at mid-stroke. This is the mover position for peak induced voltage in the coils. The plot shows three curves plotted along parallel lines which cut through the magnets: one represents a line along the inside surface

(mover side of magnet), one represents a line along the center, and one represents a line along the outside surface (stator side of magnet) of the magnet pair. Each line is parallel to the mover motion (the z-direction) and lies in the plane of the magnet symmetry. This plot shows a localized maximum demagnetization field of roughly 670 kA/m on the inside surface of the uncovered magnets. The plot also shows a field spike of 680 kA/m on the inside surface of the magnets, where the two magnets meet. This spike is due to H_z , (the H in the z-direction), as predicted by Ampere's Law. The curves for the center and outside magnet surfaces in the covered regions of the magnets show a much smaller variation in the demagnetization fields. A further refinement of the FEM mesh in this region of the model should be explored to resolve irregularities of computation.

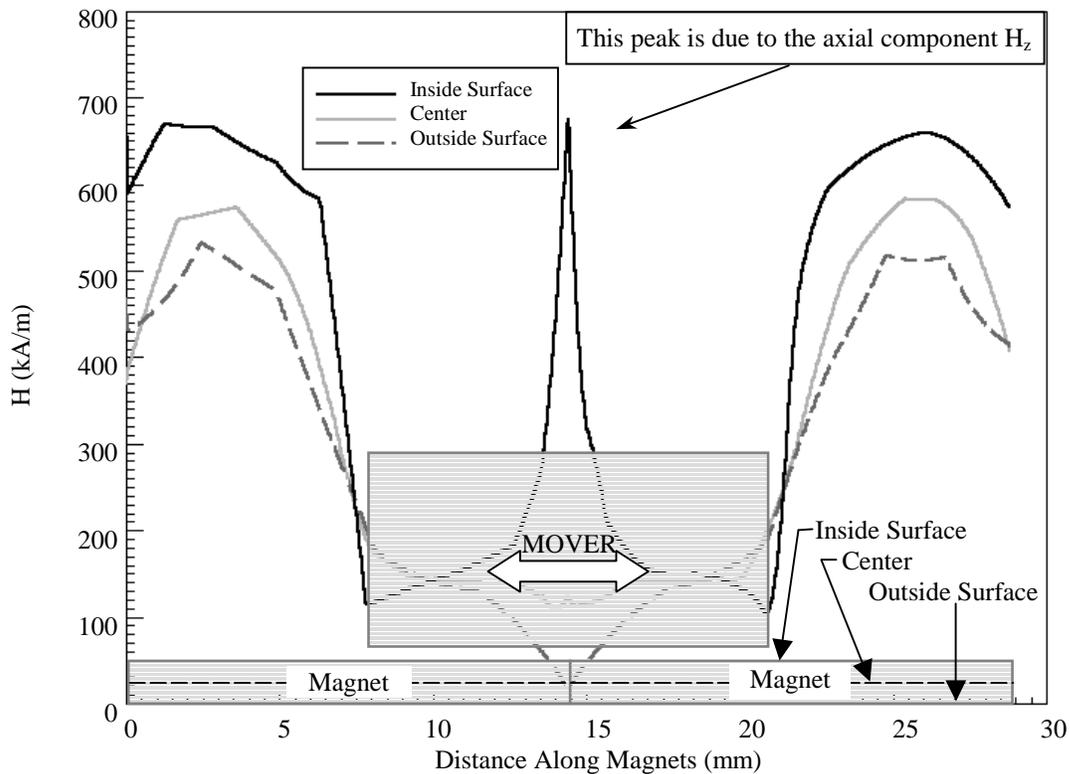


Figure 6 – Magnetic Field Strength $|\vec{H}|$ vs. Distance along Magnets at 23°C.

Average Properties at a Higher Temperature

In actual Stirling convertor applications, the magnet temperatures may reach as high as 75°C. The model was used to generate the BH trace for the magnets over a cycle at the expected operating temperature. Figure 7 shows a plot of average B vs. average H, for the alternator magnets as the mover oscillates with a 6-mm amplitude. B and H are averaged over the volume of the magnet. This plot shows that the minimum average values of B and H are 0.58 Tesla and -503 kA/m, respectively. The critical H value for the Neodymium-Iron-Boron magnets assumed in the model is approximately -750 kA/m at 75°C. For H values ≤ -750 kA/m, demagnetization may occur. Based on the large variations in the magnetic field strength seen in the magnets at the lower temperature, peak H values for localized portions of the magnets may exceed -750 kA/m at the higher temperature.

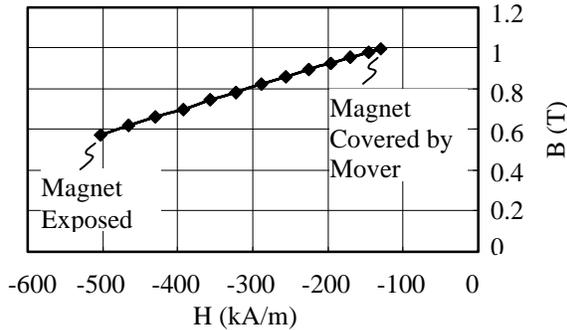


Figure 7 – Magnetic Flux Density vs. Field Strength Averaged over Magnet Volume at 75°C.

Induced Voltage

Figure 8 shows a plot of the magnetic flux linking each alternator coil as a function of mover position. Although the peak flux of 1.52E-4 Webers occurs at the ends of the mover stroke, the largest change in magnetic flux with respect to time (and therefore the largest induced emf in the coils) occurs at the mid-point of the mover stroke. The plot shows that the flux is almost linear with respect to mover position. The fact that this plot is not perfectly linear may be due to minor variations in flux fringing with mover position or it may indicate minor inaccuracies associated with the numerical solution.

The magnetostatic flux solutions were considered converged, once the energy error between iterations (as defined by the Maxwell software) became less than 2%. The 2% convergence criterion was selected as a trade-off between accuracy and computation time.

Figure 9 shows a plot of the predicted alternator open-circuit voltage as a function of time. The diamond markers show the model predictions. The solid line is a sine-wave curve fit of the points. The curve fit was used to calculate the RMS open-circuit voltage for comparison with the measured value. The shape of the voltage curve should be nearly sinusoidal. The fact that the model predictions do not lie on a sinusoidal curve may once again be due to either flux fringing variations or numerical inaccuracies (c.f. Fig. 8).

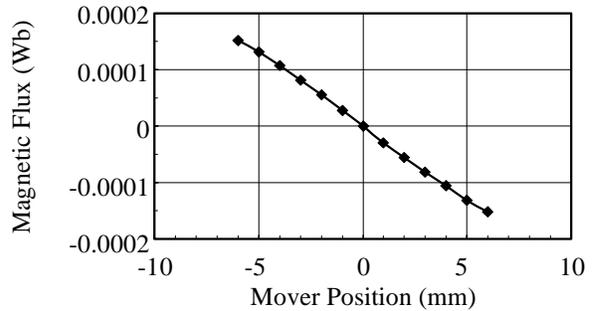


Figure 8 – Magnetic Flux vs. Mover Position at 23°C.

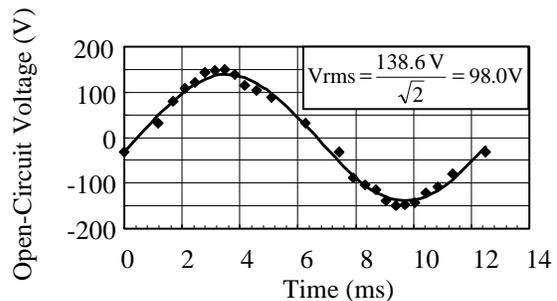


Figure 9 – Open-Circuit Voltage vs. Time at 23°C.

As with the earlier SPDE open-circuit voltage comparisons to 2-D analytical predictions, the TDC open-circuit voltage correlates closely with the new preliminary 3-D analysis. As the model is developed further and validated with more comprehensive test data, it will be an increasingly valuable design tool.

CONCLUSIONS

A commercial magnetics computation tool has been applied to develop a valuable numerical analysis model of linear alternator designs for Stirling power convertors. This model can be used to explore design variations early in the development process. However, the model needs to be further validated through additional experimentation.

The results shown by the preliminary 3-D analysis indicate that a more comprehensive analysis and measurements are appropriate for the 55W TDC linear alternator design, especially since the magnet temperatures may reach 75°C in space power applications. The portion of the magnet with the highest potential for demagnetization appears to be on the surface of the magnet pair at the edge, where the magnets are in contact with each other and adjacent to the mover. The region near an advancing/receding edge of the mover is a location where fringing fields due to load current can reinforce the already high self-demagnetizing field in the area of a magnet not adjacent to the mover. The results presented here support the need for a detailed study of load current effects in these critical regions.

Special care is needed when selecting magnets because of the high, localized demagnetizing fields. Magnets with a higher resistance to demagnetization are being used in the TDC convertors currently being fabricated by STC for NASA Glenn.

REFERENCES

1. Brown, A.T.: "Space Power Demonstrator Engine, Phase I Final Report," NASA CR-179555, 1987.
2. Dochat, G.: "SPDE/SPRE Final Summary Report," NASA CR-187086, 1993.
3. Thieme, L.G., Qiu, S., White, M.A.: "Technology Development for a Stirling Radioisotope Power System," NASA TM-2000-209791, 2000.
4. White, M.A., Qiu, S., Augenblick, J.E.: "Preliminary Test Results from a Free-Piston Stirling Engine Technology Demonstration Program to Support Advanced Radioisotope Space Power Applications," in Proceedings from STAIF-00, Space Technology and Applications International Forum-2000, Albuquerque, New Mexico, 2000.
5. Ansoft's Maxwell 3-D simulator, see World Wide Web page: www.ansoft.com
6. Niedra, J.M.: "Lightweight Linear Alternators With and Without Capacitive Tuning," NASA CR-185273, 1993.

REPORT DOCUMENTATION PAGE			<i>Form Approved</i> <i>OMB No. 0704-0188</i>	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (<i>Leave blank</i>)	2. REPORT DATE July 2000	3. REPORT TYPE AND DATES COVERED Technical Memorandum		
4. TITLE AND SUBTITLE A 3-D Magnetic Analysis of a Linear Alternator for a Stirling Power System			5. FUNDING NUMBERS WU-839-20-00-00	
6. AUTHOR(S) Steven M. Geng, Gene E. Schwarze, and Janis M. Niedra				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration John H. Glenn Research Center at Lewis Field Cleveland, Ohio 44135-3191			8. PERFORMING ORGANIZATION REPORT NUMBER E-12369	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001			10. SPONSORING/MONITORING AGENCY REPORT NUMBER NASA TM-2000-210249 AIAA-2000-2838	
11. SUPPLEMENTARY NOTES Prepared for the 35th Intersociety Energy Conversion Engineering Conference sponsored by the American Institute of Aeronautics and Astronautics, Las Vegas, Nevada, July 24-28, 2000. Steven M. Geng and Gene E. Schwarze, NASA Glenn Research Center; and Janis M. Niedra, Dynacs Engineering Company, Inc., 2001 Aerospace Parkway, Brook Park, Ohio 44142. Responsible person, Steven M. Geng, organization code 5490, (216) 433-6145.				
12a. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified - Unlimited Subject Category: 20 This publication is available from the NASA Center for AeroSpace Information, (301) 621-0390.			12b. DISTRIBUTION CODE Distribution: Nonstandard	
13. ABSTRACT (<i>Maximum 200 words</i>) The NASA Glenn Research Center and the Department of Energy (DOE) are developing advanced radioisotope Stirling convertors, under contract with Stirling Technology Company (STC), for space applications. Of critical importance to the successful development of the Stirling convertor for space power applications is the development of a lightweight and highly efficient linear alternator. This paper presents a 3-D finite element method (FEM) approach for evaluating Stirling convertor linear alternators. Preliminary correlations with open-circuit voltage measurements provide an encouraging level of confidence in the model. Spatial plots of magnetic field strength (H) are presented in the region of the exciting permanent magnets. These plots identify regions of high H, where at elevated temperature and under electrical load, the potential to alter the magnetic moment of the magnets exists. This implies the need for further testing and analysis.				
14. SUBJECT TERMS AC generators; Stirling engines; Free-piston engines			15. NUMBER OF PAGES 12	
			16. PRICE CODE A03	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT	